Spoke Cavity Cryomodule Concept for the Accelerator Driven Test Facility (ADTF) Low Energy Linac (LEL)

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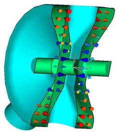

Major Contributors

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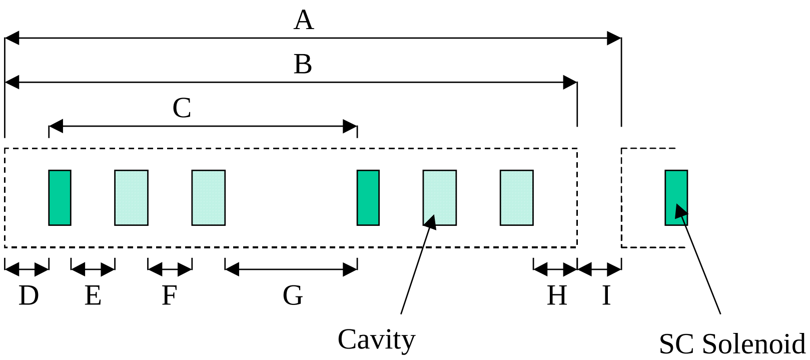
Introduction

- **The Accelerator Driven Test Facility (ADTF)**
  - **Is a reactor concepts test bed for transmutation of nuclear waste.**
  - **Uses a 13.3 mA (CW), 600 MeV linear accelerator to produce neutrons by spallation.**
- **The ADTF Low Energy Linac (LEL) uses 350 MHz superconducting (SC) spoke cavities between 6.7 - 109 MeV.**
- **Beam dynamics dictates that cavities of three β types be used:**
  - **β=0.175 two-gap cavities,**
    - » **A β=0.175 lattice element consists of a solenoid magnet and two cavities**
    - » **The focussing period is 2.26 m**
  - **β=0.2 and β=0.34 three-gap cavities,**
    - » **the lattice consists of a solenoid magnet and three cavities.**
    - » **The focussing periods are 3.05 and 3.46 m respectively.**

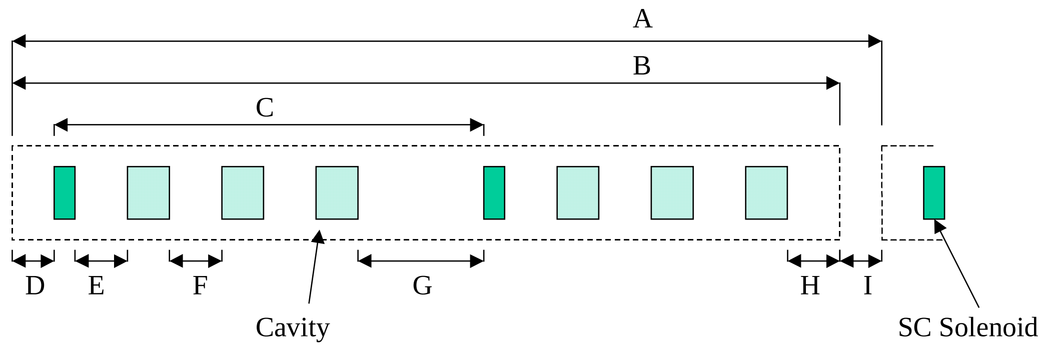
Spoke-Cavity Cryomodule Period

- **The cryomodule period was dictated by:**
  - **The need to reduce LEL length and total system costs by minimizing distances between elements.**
    - » **This led to inclusion of the solenoids as SC elements in the cryomodule.**
  - **The need for periodic warm spaces for beam diagnostics.**
  - **The desire to maximize cryomodule lengths to**
    - » **minimize the total number of warm to cold transitions,**
      - **reduce heat loads and cryogenic distribution system complexity.**
  - **The need to fit the module elements into the existing clean room.**

Spoke-Cavity Cryomodule Period

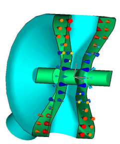


ß=0.175 Cryomodule



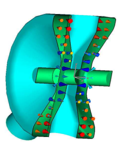
ß=0.2 or 0.34 Cryomodule

		β=0.175	**β=0.2**	**β=0.34**
Cryomodule Period	A	4.53 m	6.10 m	6.92 m
Cryomodule Length	B	4.23 m	5.80 m	6.62 m
Focusing Period	C	2.26 m	3.05 m	3.46 m
Warm to Cold Transition (1)	D	0.39 m	0.39 m	0.39 m
Magnet to Cavity Drift	E	0.3 m	0.3 m	0.3 m
Cavity to Cavity Drift	F	0.3 m	0.3 m	0.3 m
Cavity to Magnet Drift	G	1.11 m	1.11 m	1.11 m
Warm to Cold Transition (2)	H	0.42 m	0.42 m	0.42 m
Cryomodule to Cryomodule Drift	I	0.3 m	0.3 m	0.3 m
Magnet Physical Length		0.15 m	0.15 m	0.15 m
Cavity Physical Length		0.20 m	0.30 m	0.43 m



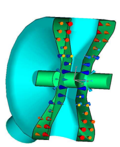
Spoke-Cavity Cryomodule Parameters

	β=0.175	β=0.2	β=0.34
Q_o	1.72 E 9	1.92 E 9	2.50 E 9
E_{acc}	5 MV/m	5 MV/m	5 MV/m
Frequency	350 MHz	350 MHz	350 MHz
Coupled Power @ 13.3mA(100 mA)	4.7 (35.3) kW	10.35 (77.8) kW	18.6 (139.8) kW
Cavity Operating Temperature	4.5 K	4.5 K	4.5 K
Cavity External Magnetic Field (Goal)	5 milli-Gauss	5 milli-Gauss	5 milli-Gauss
Cavity Mechanical Resonance	> 200 Hz	> 200 Hz	> 200 Hz
Tuning Stiffness	~ 26 kHz/mil 0.31 kHz/lb.	To Be Determined	To Be Determined
Cavity Detuning Rate in < 300 msec	67 kHz/sec 67 micron/sec	To Be Determined	To Be Determined
Shield Operating Temperature	40-55 K	40-55 K	40-55 K
Solenoid Field	1.8-2.32 T	2.5-4.0 T	4.0-5.4 T
Current	20 A	20 A	20 A
Lead Type	Conduction Cooled	Conduction Cooled	Conduction Cooled



Cryomodule Design Goal and Guidelines

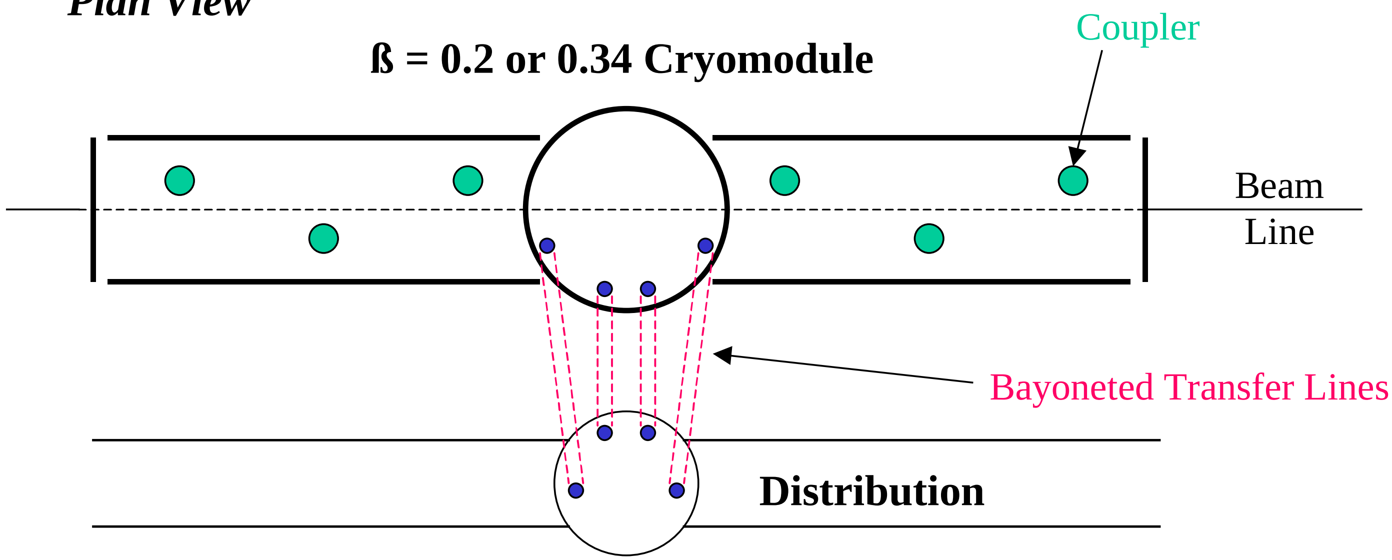
- **Goal: Provide a cryomodule design that can easily be built by industry.**
- **Focus of Presentation**
  - **ß = 0.34 Spoke Cavity Cryomodule.**
    - » **Elements are similar for all ADTF spoke cavity cryomodules.**
- **Basic guidelines used during cryomodule design development :**
  - **Adopt concepts and components from previous programs where possible.**
  - **Insert helium vessel assemblies axially into the vacuum vessel.**
    - » **Minimizes cleanroom time and simplify assembly**
    - » **Minimize radial penetrations is a corollary.**
  - **Adopt design similarity between the three module types.**
    - » **With the exception of length, parts should be identical.**
  - **Since ADTF has it roots in the Accelerator Production of Tritium Program (APT),**
    - » **It must be upgradable to 100 ma operations for tritium production.**
    - » **The ADTF cryomodule must fit into the APT tunnel design.**
      - **(After the completion of this work, this requirement was eliminated.)**



Spoke Cavity Cryomodule Form

- **Physical Form**
  - **Ingress and egress of cryogens at center of module**
    - » **Permits axial assembly approach**

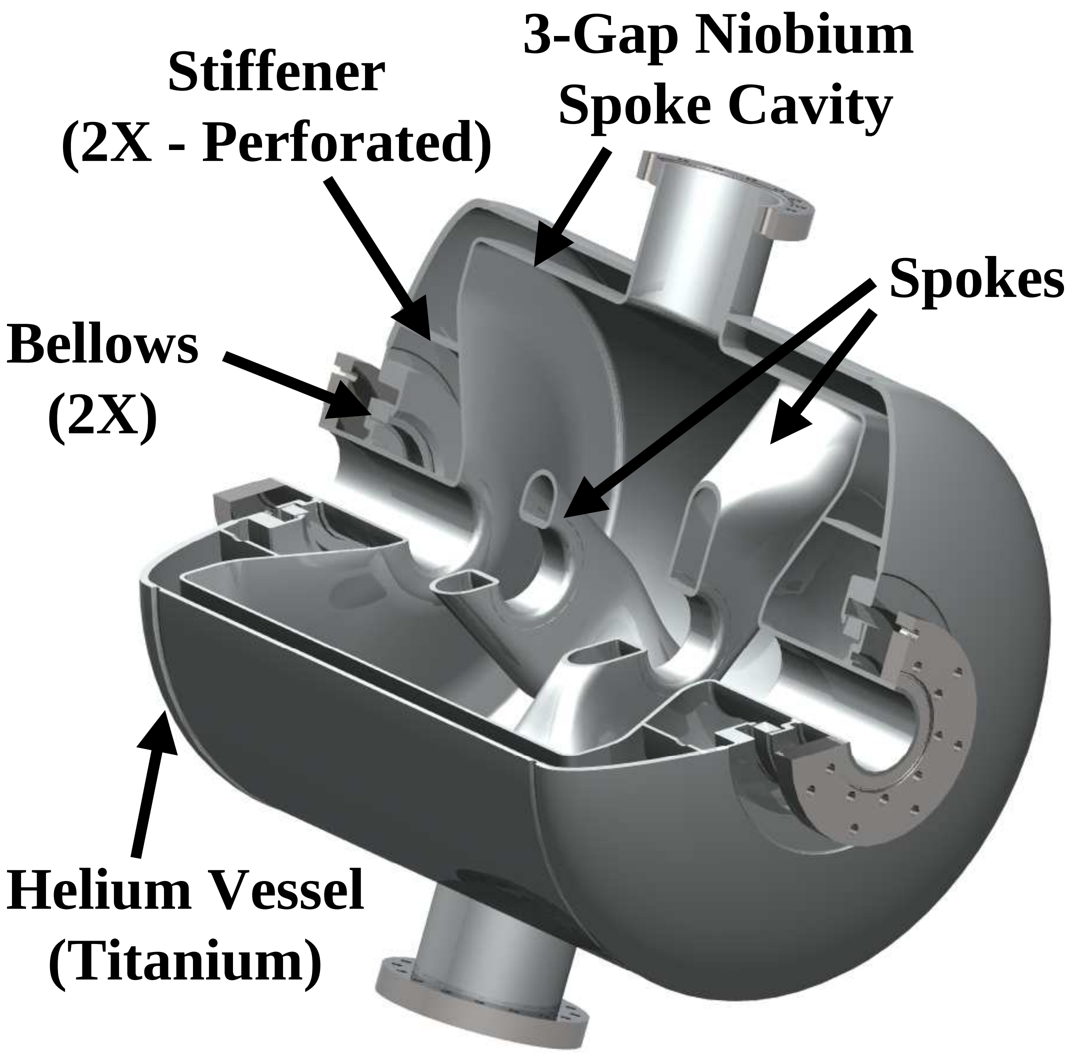
Plan View



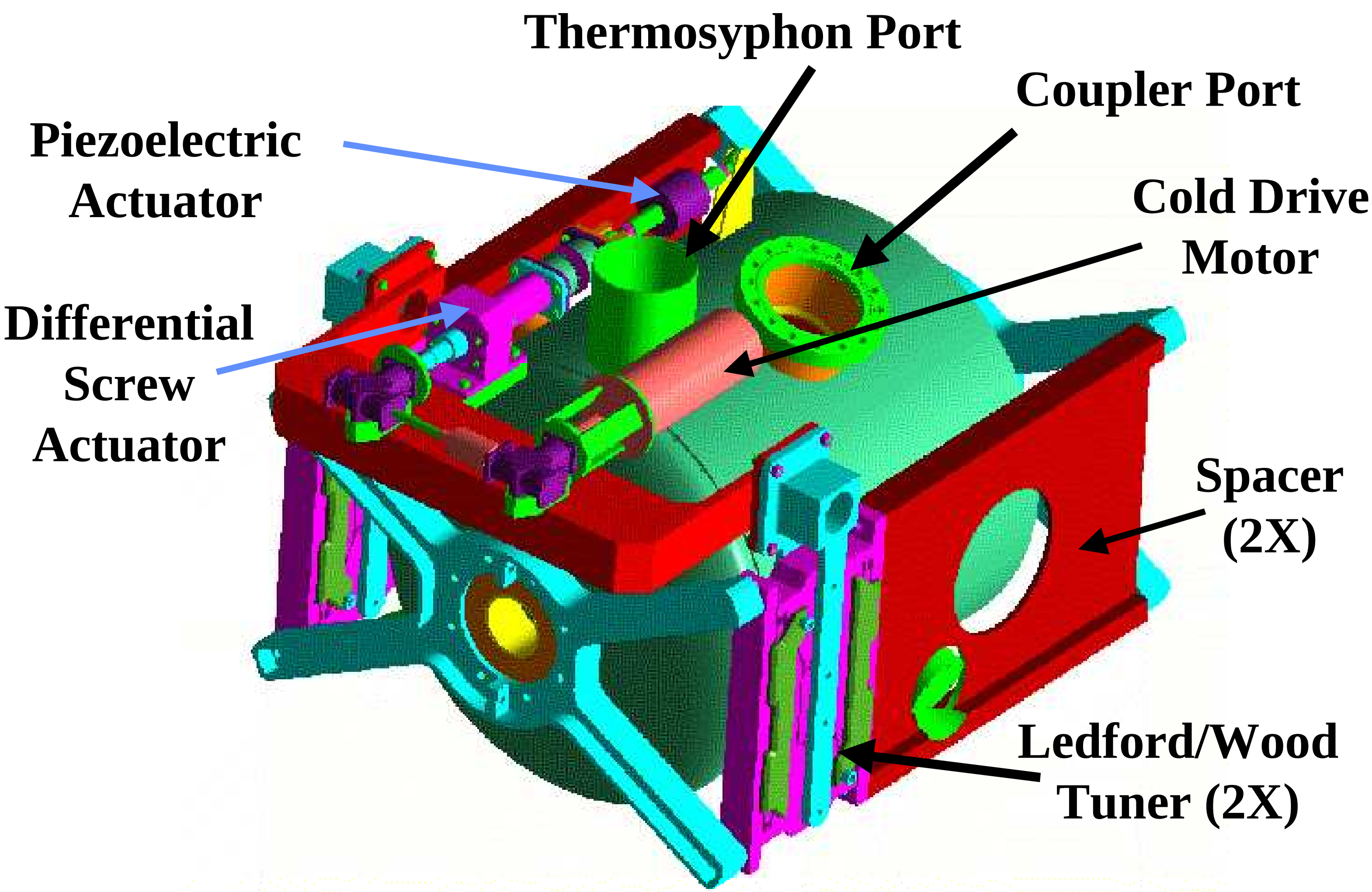
Tuners and Helium Vessels

- **Cavities are tuned individually.**
  - **Both end walls of a spoke cavity must be flexed**
    - » **Tuner assembly must straddle the cavity.**
- **A cavity is housed in its own titanium helium vessel with the tuner outside the vessel.**
  - **If both cavity and tuner were housed in a helium vessel**
    - » **Helium vessel size would increase,**
    - » **Essentially flat helium vessel heads would be necessary to minimize spacing between cavities, leading to thicker material or elaborate stiffeners.**
    - » **Multiple cold penetrations would be required.**
  - **If multiple cavities with tuners were housed in a single vessel,**
    - » **The length dictates elaborate penetrations to handle thermal contractions.**
- **A Ledford/Wood tuner mechanism (APT program) was adopted.**
  - **The cavity stiffeners are used to transfer loads through the helium vessel.**
  - **Bellows are used to de-couple the beam tube from the helium vessel.**
  - **A cold stepper motor drives tuner. (Warm motor/axial drive shaft possible.)**
  - **A piezoelectric actuator is used to detune the cavity in < 300 msec.**

3-Gap Spoke Cavity with Helium Vessel



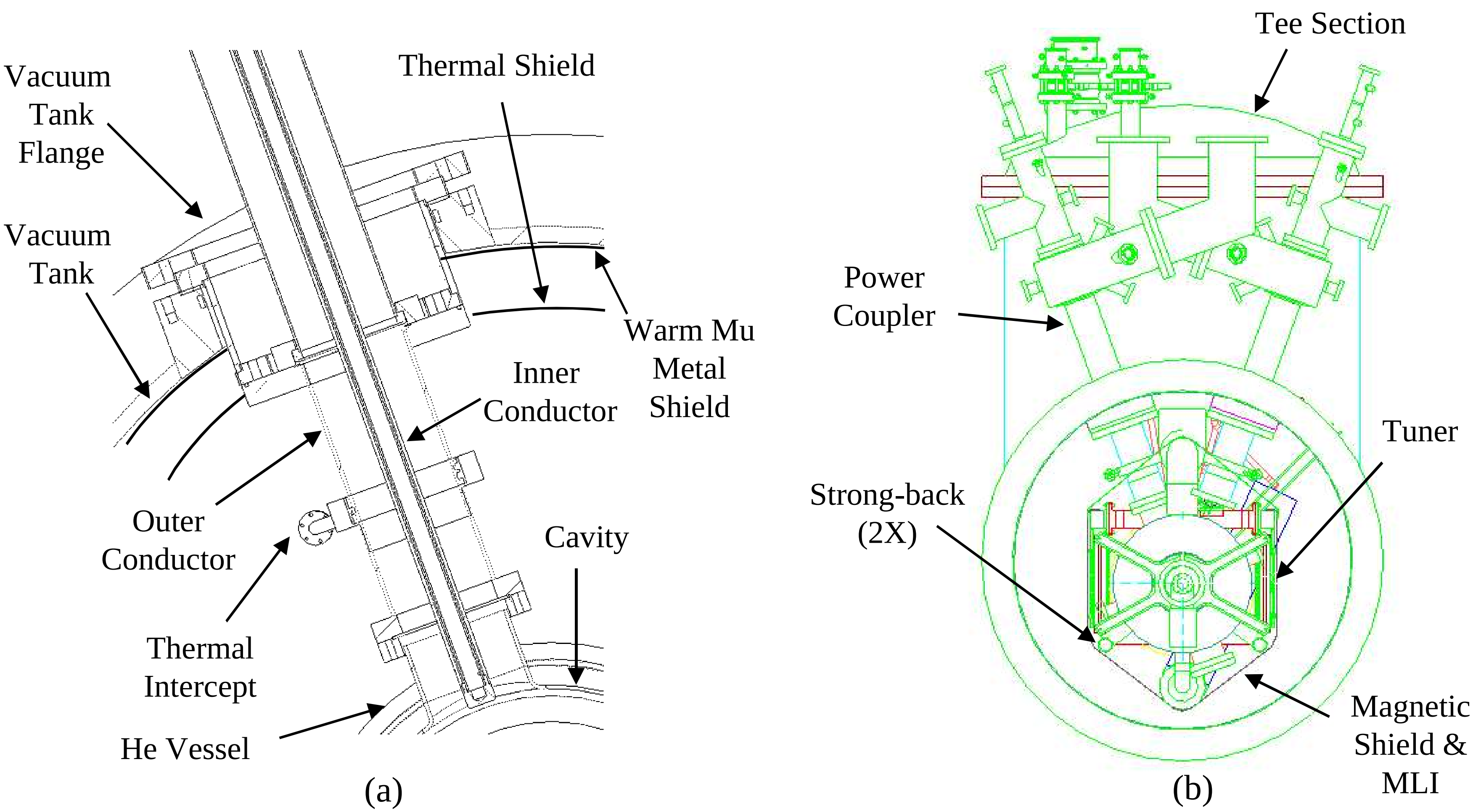
ß = 0.34 Spoke Cavity Helium Vessel with Tuner Assembly



Power Coupler

- The fixed power coupler is a 75 Ω, coaxial, unbiased unit.
- Couplers are oriented 20° from vertical, with adjacent couplers in a lattice on alternate sides of the module. The couplers closest to the center Tee section are on the same side of the module.
  - The near vertical orientation was due to APT tunnel constraints.
  - The alternating sides coupler arrangement is necessary to maintain clearance between large WR2300 waveguides (0.584 X 0.146 m.).
- Heat loads were calculated for a single point thermal intercept
- The coupler is also the only helium vessel assembly support structure, therefore simplifying assembly.
  - Assembly is simplified with fewer penetrations through shields and blankets. Fewer penetrations through the magnetic shields reduces magnetic-fringe fields.

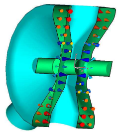
Power Coupler



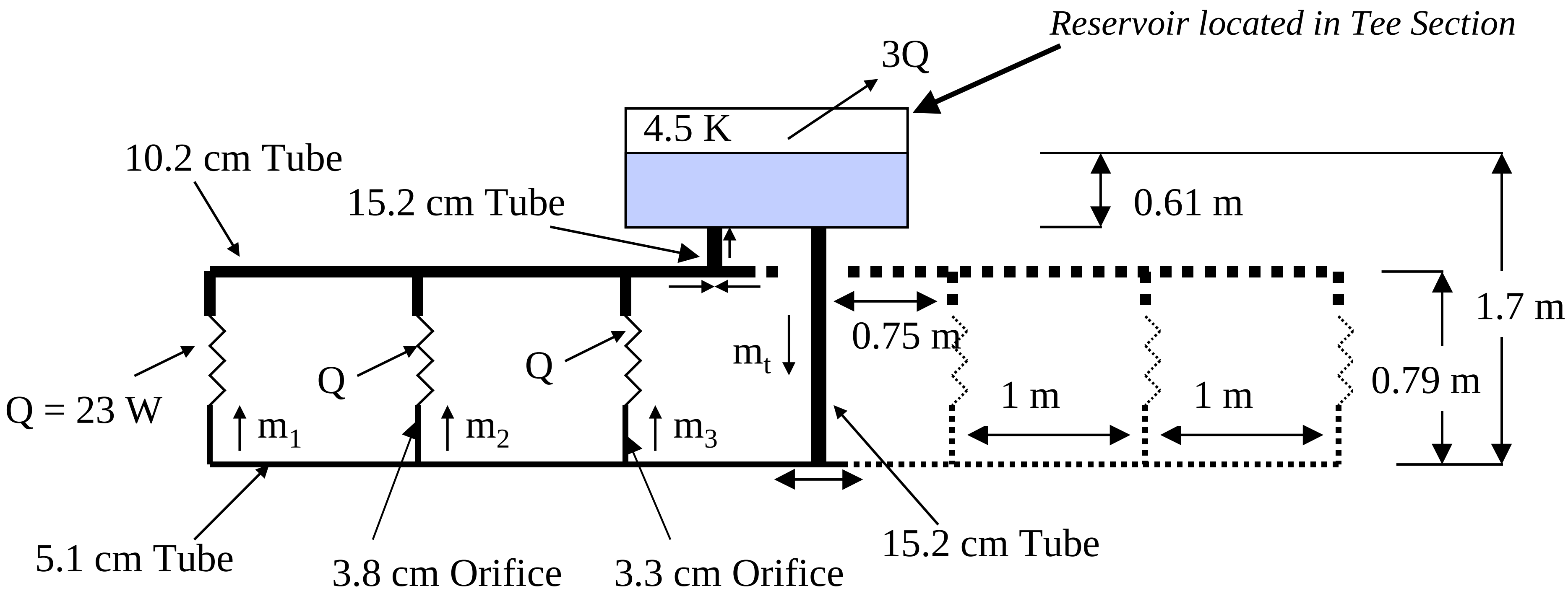
(a) Coupler - vacuum vessel interface. (b) Cryomodule section. Warm shields not shown.

Cavity Cooling Approach - A Thermosyphon

- **An open-loop thermosyphon cooling approach was selected to cool the spoke cavities.**
  - **Individual helium vessels limits the volume available for helium inventory.**
  - **At 4.5 K, bath cooling has better heat transfer properties than supercritical forced flow.**
    - » **boiling of the helium is anticipated with the potential for vapor trapping/locking.**
  - **A thermosyphon**
    - » **deals well with space constraints,**
    - » **provides reasonable helium inventory,**
    - » **reduces the potential for vapor locking and**
    - » **improves heat transfer through localized forced flow.**



Thermosyphon Analysis - 0.34 β Cryomodule



m_1 = 35.3 g/s, χ_1 = 0.028
m_2 = 35.2 g/s, χ_2 = 0.029
m_3 = 34.9 g/s, χ_3 = 0.029
m_t = 210.9 g/s

All tube 0.165 cm wall

Orifice plates balance flows through the legs.

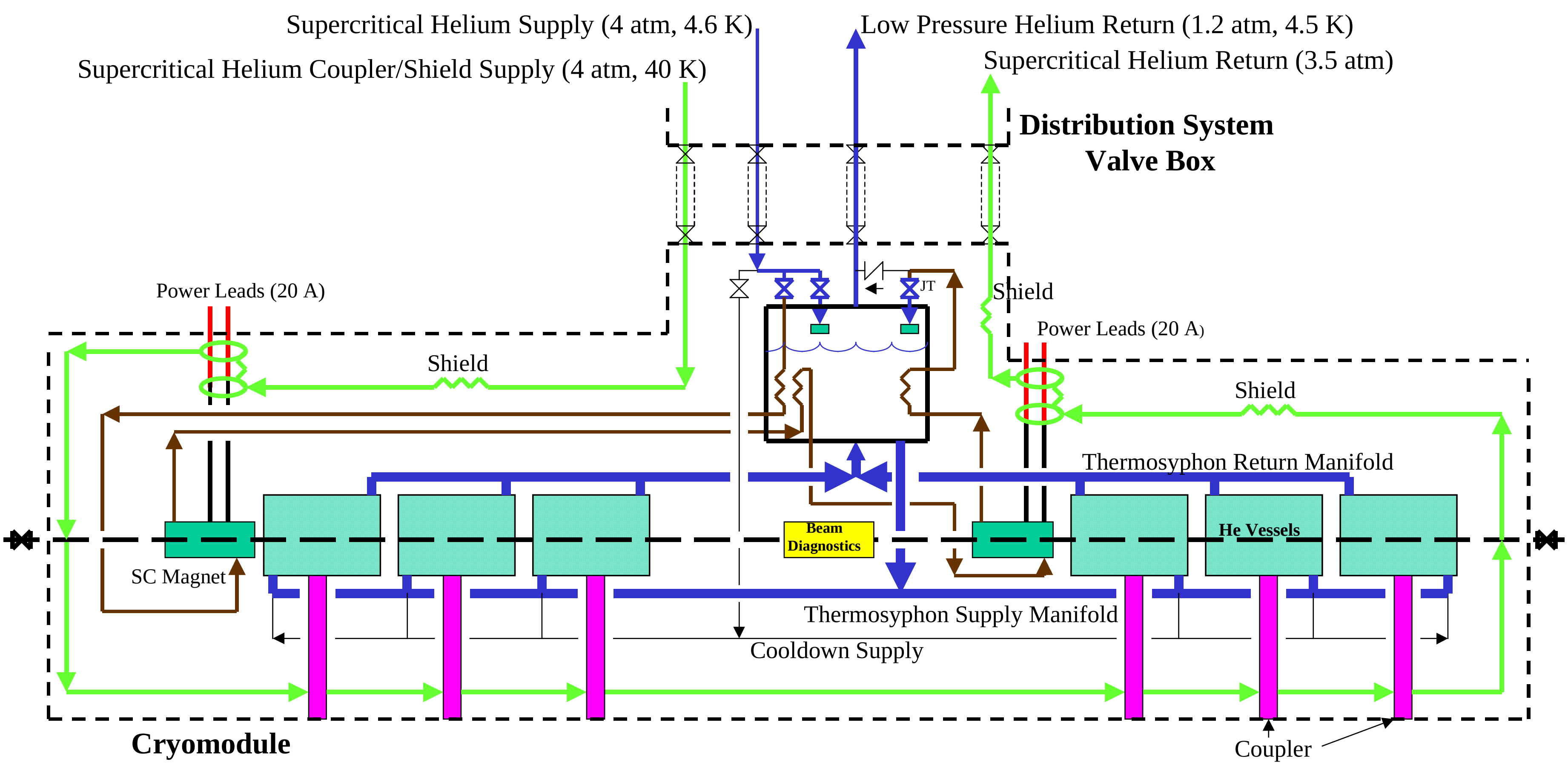
χ - flow quality

Bellows in the runs between risers were included in the analysis but are not shown.

Cryogen Supply

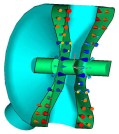
- Supercritical helium at 4.6 K and 4 atm is supplied to the module
  - The flow is split
    - » A portion expanded by a JT valve to fill the thermosyphon reservoir.
    - » The remaining flow is recooled and directed serially to the solenoids.
      - A recooler between magnets is sized so that the downstream magnet is not impacted by an upstream magnet quench.
      - A recooler after the downstream magnet removes quench or other heat from the flow, allowing the return of useful cold gas to the cryoplant.
      - The supercritical flow is then throttled to thermosyphon reservoir pressure to provide liquid, and to eliminate the need for a separate return line in the distribution system.
- The shields and intercepts are cooled by a flow of supercritical helium at 4 atm. and 40 < T < 55 K.
  - Current leads are conductively cooled with a 40 K intercept.

Spoke Cavity Cryomodule - Flowsheet

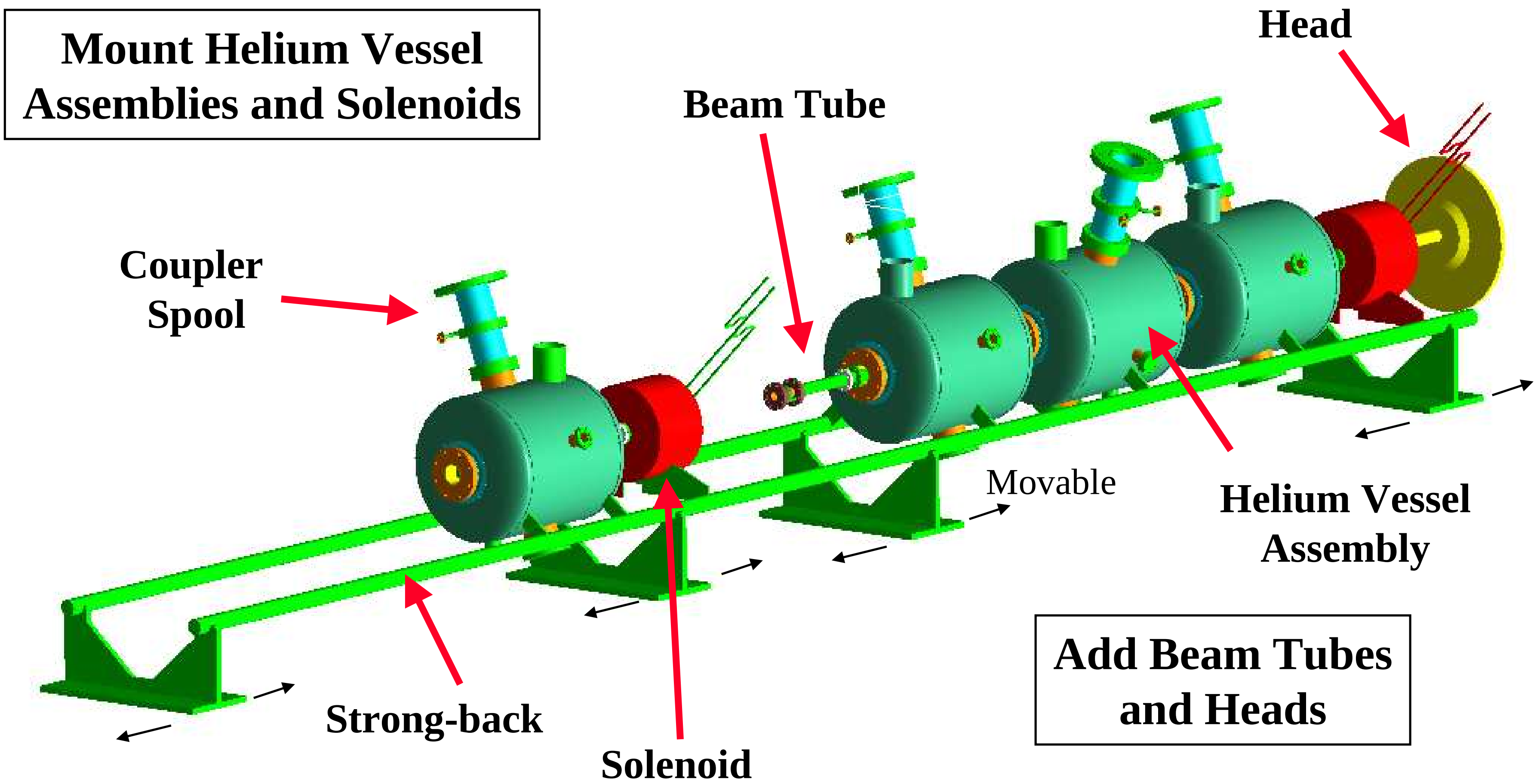


Spoke Cavity Cryomodule Clean Room Assembly

- Known - relative positions of beam center line, coupler inner flange and foot pads.
- Helium vessel assemblies (cavity/coupler/helium vessel)
  - Are mounted on pre-aligned strong-back
  - Fiducials are added to outer coupler flanges (for relating position of beam tube centerline to coupler outer flange)
  - Beam tubes are installed.
  - Temporarily locked-down to strong-back
- Solenoid magnet assemblies
  - Are mounted on the strong-back.
  - Beam tubes are installed (cavity to solenoid, solenoid to ambient).
- Transfer alignment data to fiducials on outer coupler flanges
- Final lock-down to strong-back



Spoke Cavity Cryomodule Clean Room Assembly - Figure



Spoke Cavity Module Final Cold Mass Assembly

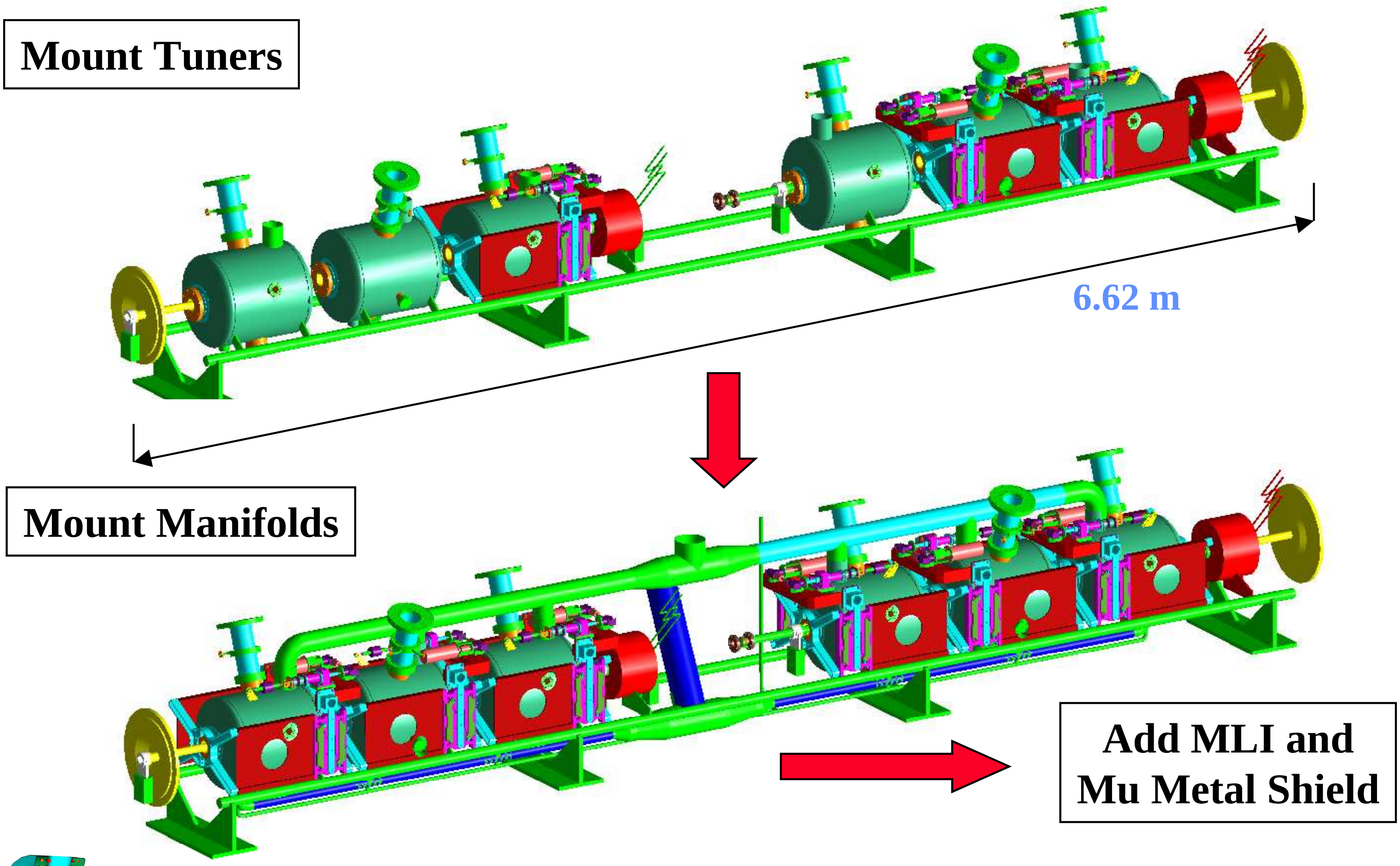
- Remainder of assembly performed outside the clean room

- Mount tuner assemblies
  - Tuner - Same as the APT Tuner
  - Cold Motor - Saclay-TESLA-SNS Pedigree
  - Piezoelectric actuator
    - » Allows for cavity detuning in < 300 msec.

- Mount manifolds
  - 2” tube supply, 4” tube return, 1/2” tube cooldown supply

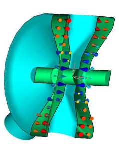
- Add multilayer insulation blanket (MLI - 15 layers) and Mu metal shield (0.040” thick)

Spoke Cavity Module Final Cold Mass Assembly - Figure



Spoke Cavity Module Final Assembly

- Insert cold mass assembly into prefabricated Tee section
  - Tee thermal shield (Cu), magnetic shield (Mu metal - 0.040”) & MLI blankets (4 @ 15 layers ea.) preinstalled.
- Mount vacuum vessel cylinders to Tee section
  - Thermal shield, MLI blankets, magnetic shield preinstalled (similar to CEBAF’s approach).
  - Thermal shield & MLI blanket bridges made.
- Mate couplers/solenoids to vacuum vessel
  - Couplers are only mechanical support for helium vessel assemblies
  - Solenoids use compression post support
    - » Similar posts used by SSC, RHIC, LHC
- Remove strong-back
- Install current lead feedthroughs
- Install Tee-section head/internals - make pipe connections
- Install end caps



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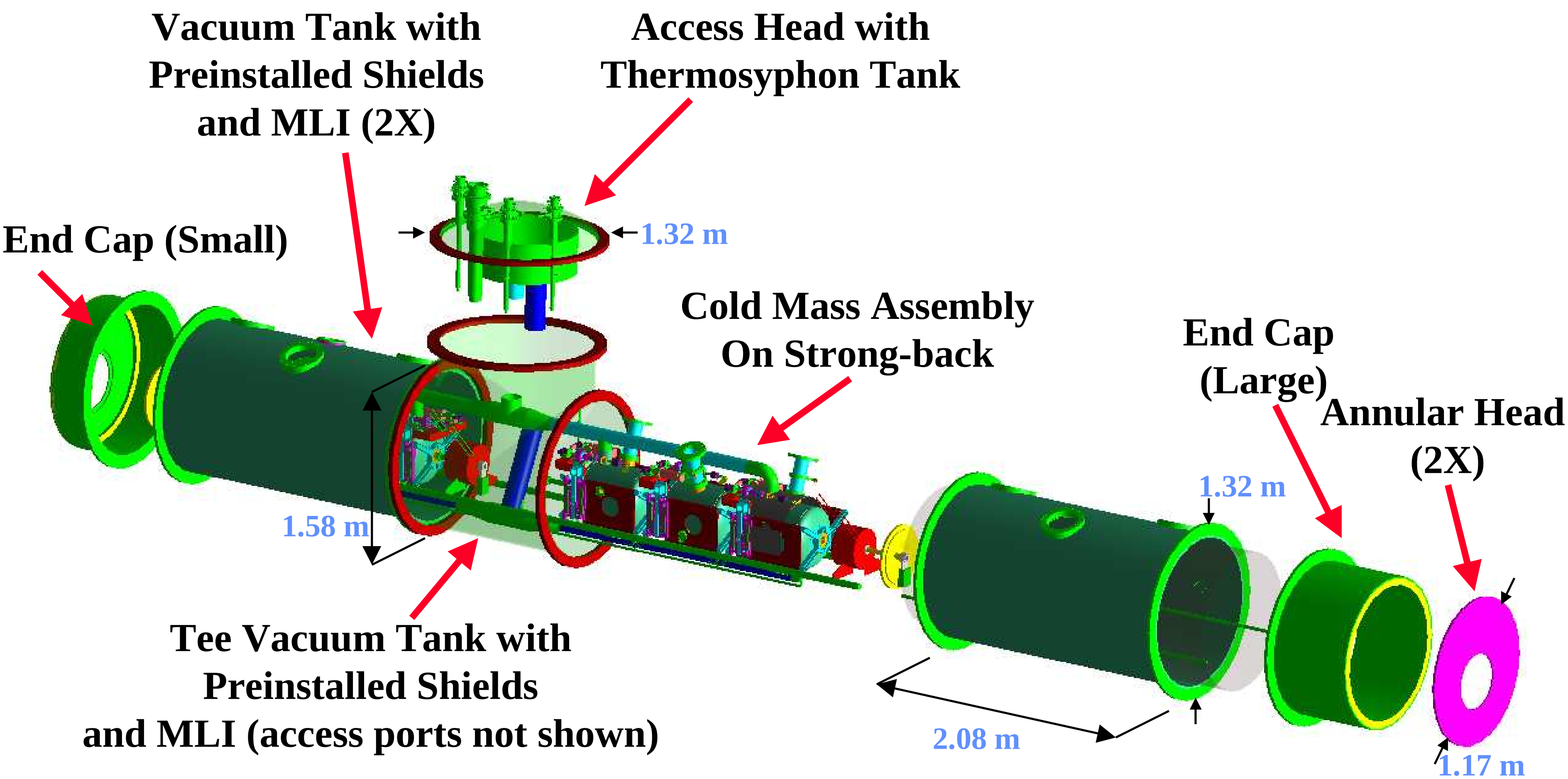
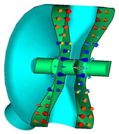
Spoke Cavity Cryomodule Final Assembly - Figure



Spoke Cavity Cryomodule Summary

- Adopted concepts and components from previous programs - minimize risk.
- Thermosyphon cooling - improves thermal performance.
- Coupler supported cavities
  - simplifies assembly,
  - minimizes thermal shorts, magnetic fringe fields, and
  - reduces part count.
- Axial insertion
  - minimizes clean room time and
  - simplifies assembly.
- Similar work has been done by industry.



Back-up Slides

Section 4 (Largest) Solenoid Magnet Dimensions and Parameters

- **Electrical Parameters**
  - Current – 20 A
  - Inductance – 280 H
  - Power Supply Voltage – 20 V
  - Field @ Centerline – 6 T
  - Field 6.5 cm from end of windings - < 0.1 T
  - Charge time – 280 sec.
  - Stored Energy – 56 kJ
- **Physical Parameters**
  - Cold Bore Diameter – 11 cm
  - Active Length – 30 cm
  - Diameter of Windings – 15.3 cm
- **Leads – Conduction Cooled**
  - Intercepted at the shield temperature

Largest Solenoid Magnet Dimensions and Parameters

- **Cooling (Steady State and Cooldown) – Supercritical He @ 4.5 K, 4 atm.**
- **Quench**
  - **Magnet goes normal in ~ ½ second.**
  - **Temperature reaches ~ 185 K**
  - **Boiloff at 4.5 K sat. ~ 23 L**
  - **Recovery Time – System Dependent**
  - **Note – Segmenting or some other approach will be necessary to minimize internal voltages generated during quench.**

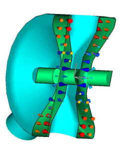
Spoke Cavity Coupler Heat Loads*
(100 milliamps - No Margin)

	RF On	RF On	RF On	RF Off
Inner Conductor Cooling Temp.	300 K	300 K	300 K	300 K
Tunnel/Compressor Water Temp.	300 K	300 K	310 K	300 K
Intercept Temp.	40 K	50 K	40 K	40 K
4.5 K Heat Load	3.8 W	4.7 W	3.8 W	3.3 W
Intercept Heat Load	20.6 W	19.2 W	21.7 W	20.5 W
Wall Power	1436 W	1549 W	1512 W	1303 W

*Waynert, Joe, *Thermal Analysis on ADTF Spoke Cavity Power Coupler*, ESA-EPE:01-075, March 30, 2001.

Spoke Cavity Cryomodule Preliminary 4.5 K Heat Loads (100 milliamps - no margin)

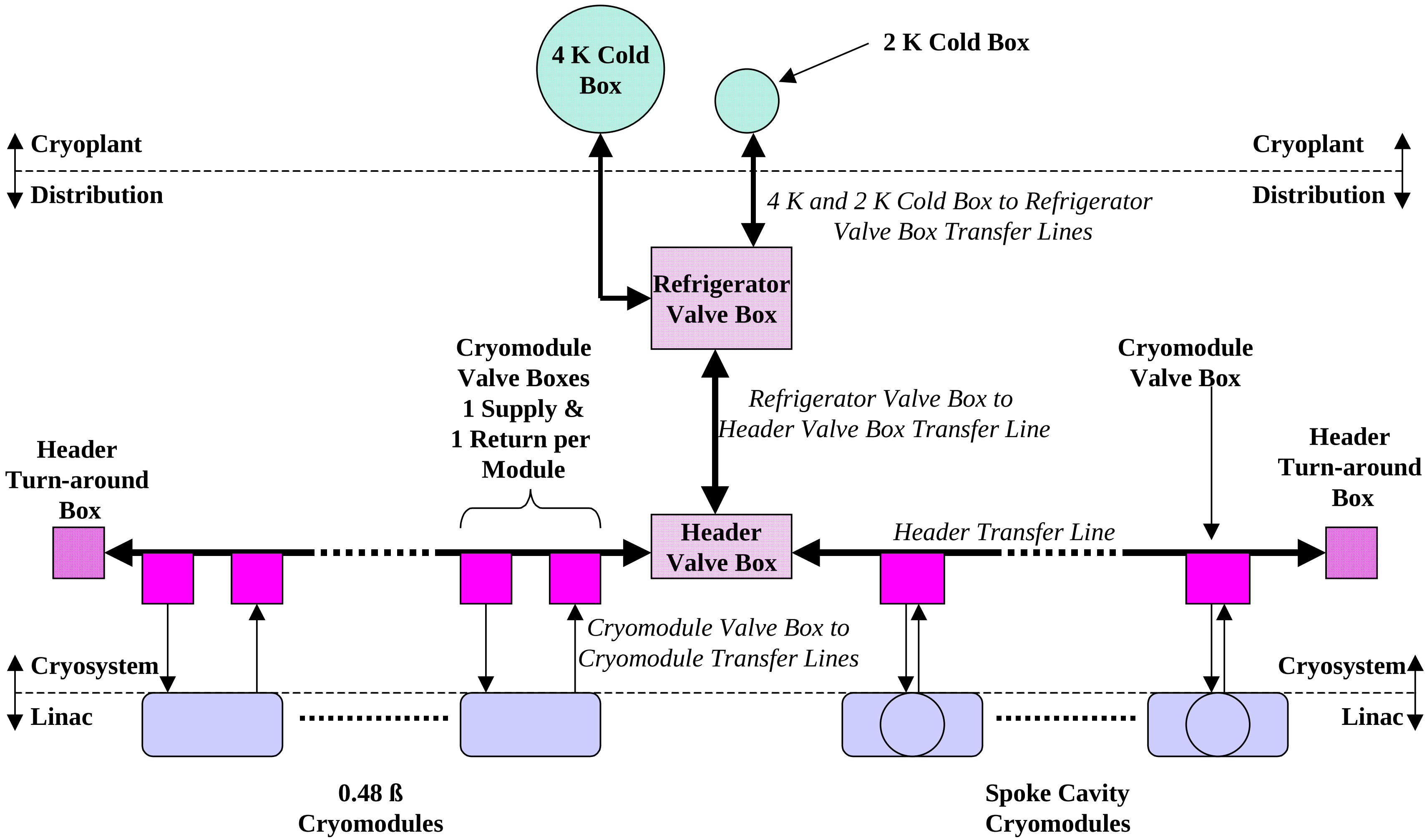
	β = 0.175			β = 0.2			β = 0.34		
Unit	**# Units**	**H.L/Unit**	**Tot. H.L.**	**# Units**	**H.L/Unit**	**Tot. H.L.**	**# Units**	**H.L/Unit**	**Tot.H.L.**
Cavity (Krawczyk)	4	2.85	11.4	6	8.37	50.22	6	14.64	87.84
Couplers (Waynert)	4	4	16	6	4	24	6	4	24
Beam Tube (Waynert)	2	0.7	1.4	2	0.7	1.4	2	0.7	1.4
Current Lead Pair - 20 A (Weisend)	2	0.4	0.8	2	0.4	0.8	2	0.4	0.8
Radiation (0.02 W/m^2)	17.23	0.02	0.34	22.89	0.02	0.46	25.84	0.02	0.52
Small Male & Female Bayonets	3	0.41	1.23	3	0.41	1.23	3	0.41	1.23
Large Male & Female Bayonet	1	1.7	1.7	1	1.7	1.7	1	1.7	1.7
Valves (used APT Value for JT)	4	0.25	1	4	0.25	1	4	0.25	1
Relief Lines (small)	2	0.024	0.047	2	0.024	0.047	2	0.024	0.047
Relief Lines (large)	1	0.14	0.14	1	0.14	0.14	1	0.14	0.14
Cables (used APT value)	1	0.7	0.7	1	0.7	0.7	1	0.7	0.7
Solenoid Supports (CERN LHC Post)	2	1	2	2	1	2	2	1	2
Strong-back Supports (CERN LHC Post)	4	1	4	4	1	4	4	1	4
HOMs ($\leq$ 2 W TBD - Krawczyk)	4	2	8	4	2	8	4	2	8
Total 4.5 K Heat Loads			**48.76**			**95.70**			**133.38**



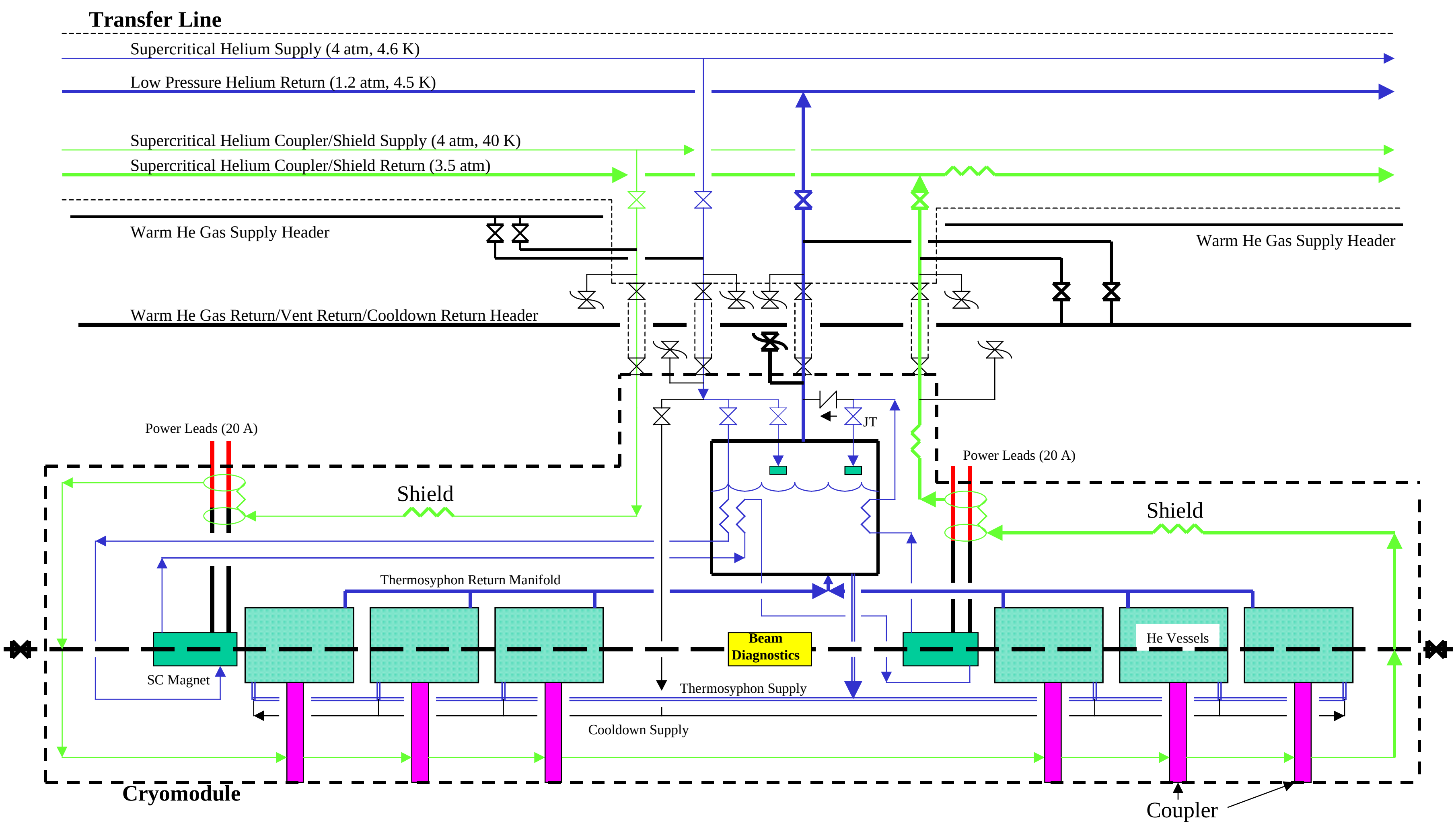
Spoke Cavity Cryomodule Preliminary Shield Heat Loads (100 milliamps - no margin)

	β = 0.175			β = 0.2			β = 0.34		
Unit	**# Units**	**H.L/Unit**	**Tot. H.L.**	**# Units**	**H.L/Unit**	**Tot. H.L.**	**# Units**	**H.L/Unit**	**Tot.H.L.**
Cavity (Krawczyk)	4	0	0	6	0	0	6	0	0
Couplers (Waynert)	4	20.6	82.4	6	20.6	123.6	6	20.6	123.6
Beam Tube (Waynert)	2	1.47	2.94	2	1.47	2.94	2	1.47	2.94
Current Lead Pair - 20 A (Weisend)	2	1.6	3.2	2	1.6	3.2	2	1.6	3.2
Radiation (1 W/mA^2)	17.23	1.00	17.23	22.89	1.00	22.89	25.84	1.00	25.84
Small Male & Female Bayonets	3	0.75	2.25	3	0.75	2.25	3	0.75	2.25
Large Male & Female Bayonet	1	2.56	2.56	1	2.56	2.56	1	2.56	2.56
Valves (used APT Value for JT)	4	2.5	10	4	2.5	10	4	2.5	10
Relief Lines (small)	2	0.425	0.850	2	0.425	0.850	2	0.425	0.850
Relief Lines (large)	1	2.551	2.551	1	2.551	2.551	1	2.551	2.551
Cables (used APT value)	1	2	2	1	2	2	1	2	2
Solenoid Supports (CERN LHC Post)	2	8	16	2	8	16	2	8	16
Strong-back Supports (CERN LHC Post)	4	8	32	4	8	32	4	8	32
HOMs	4	0	0	4	0	0	4	0	0
Total Shield Heat Load			**173.98**			**220.84**			**223.79**

LEL Refrigeration - Conceptual Layout - APT Type ß = 0.48 Cryomodule



Spoke Cavity Cryomodule Interface to Distribution System Flowsheet



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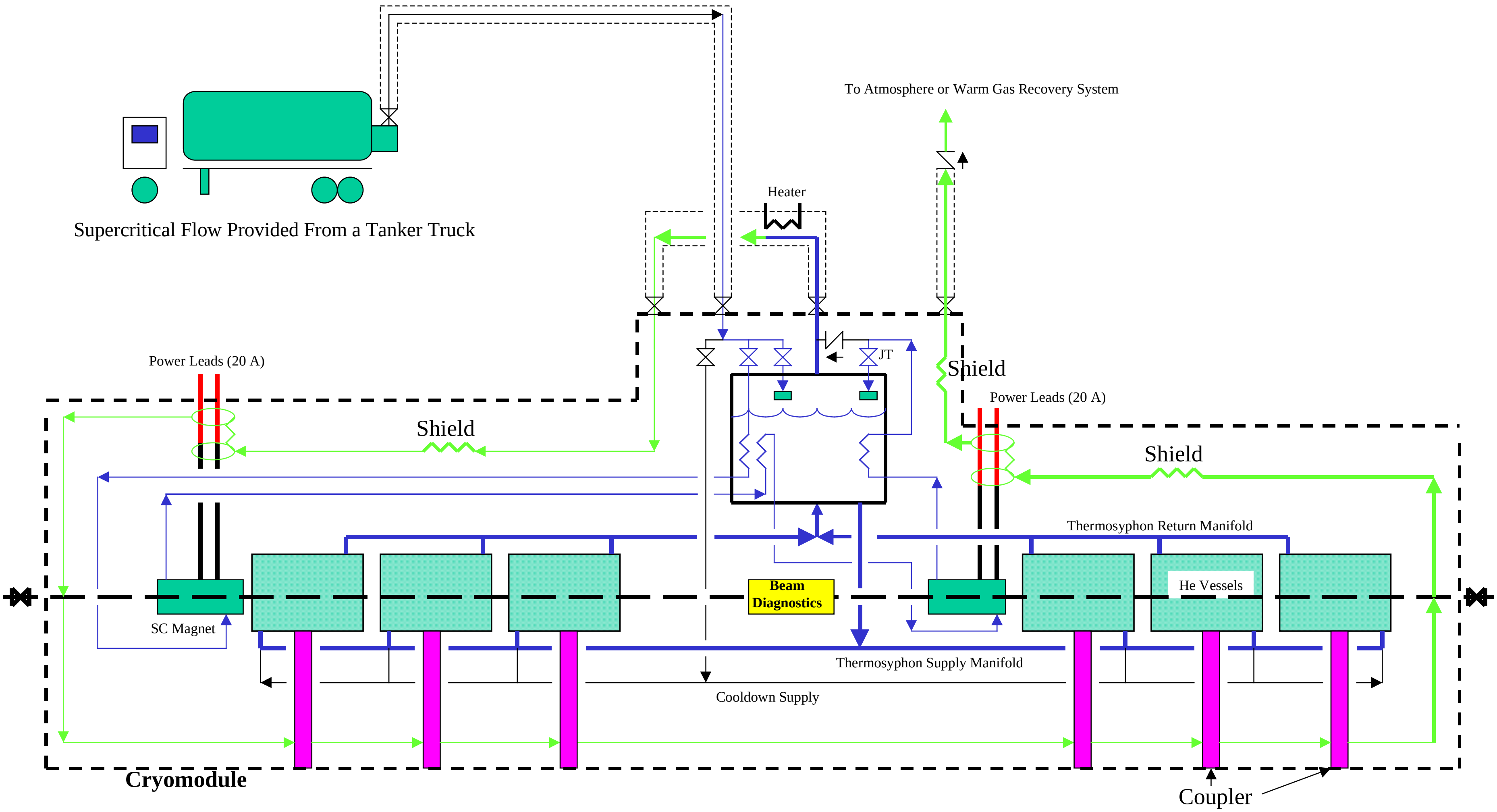
Spoke Cavity Module Test Flowsheet



ß = 0.48 Cryomodule - Flowsheet